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project

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Engineering Specification

D3 (MBRS) – DIPOLE COOLING SCHEME

Abstract

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5, and 8) and the RF Insertion (IR 4). The D3 twin aperture dipoles are utilized in the RF insertions. The D3 dipoles are cooled at 4.5 K. This specification establishes the requirements and interfaces for the cooling of the D3 dipoles.

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History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
0.1 – draft		All	First Draft
0.2 – draft		All	Added material thoughout
0.3 – draft	2001-02-27	All	Updated field/field-free lengths from Rob's 30Jan01 tables. Updated heat loads. Updated text throughout.

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1. OVERVIEW

Twin aperture superconducting beam separation dipoles MBRS (lattice designation D3a and D3b), MBRA (D4a) and MBRB (D4b) are used to increase the separation of the beams of the LHC. The beams are increased from the nominal spacing of 194 mm to 420 mm so that individual RF cavities can be installed at Insertion Region 4 (IR4) for each beam [1]. This specification refers only to the cooling requirements and interfaces of the MBRS dipoles and their LBRS cryo-assemblies.

1.1 LOCATION

Each MBRS dipole (D3a and D3b) consists of two , single aperture, RHIC-type cold masses in a single cryostat [2]. Each 10 meter long MBRS magne is the same except for the separation of the beam tubes (420 mm for D3a and 382mm for D3b). The MBRS dipoles are installed in IR4 between the Q6 magnet and the DFB feed box. A sketch of the left side of this region is shown in Figure 1.

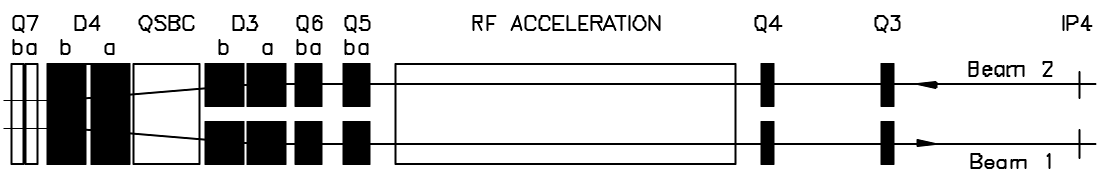


Figure 1. Geometry in the RF Region of the LHC. The nominal 194 mm separation of the beams is increased to 420 mm so that there is space for independent RF acceleration cavities for the two beams.

1.2 COOLING

Together as an LBRS (D3) cryo-assembly, D3a and D3b represent one cryogenic module 20 m in length [4]. There is an elevation change of –7.2 cm between two ends of the module, due to the –0.36 % slope at IR 4. The cooling of the cold mass, heat shield and beam screen are in series between D3a and D3b.

Although most of the LHC magnets are operated at a temperature of 1.9 K, the D3 magnets can easily provide the necessary field strength for the LHC when operated at 4.5 K. They are operated at 4.5 K to minimize the use of 1.9 K resources.

Headers C and D in the LHC cryogenic distribution line are used to provide a bath of liquid helium at 4.5 K. The lowest temperature of this cooling scheme is 4.5 K due to the 1.3 bar operating pressure of the D Header. The pool boiling cooling scheme use for the LBRS cryo-assembly has considered cryogenic module, tunnel slope, magnet geometry and liquid control.

For pool boiling cooling, helium vapor must be vented from the high elevation end of the module. To provide suitable cooling for the long magnet during cooldown, the helium supply is introduced at the low elevation which is the opposite end of the magnet. Thus helium flows completely through the magnets during cooldown and warmup.

For steady state operation, liquid helium is fed from the high elevation end to prevent helium vapor, occurred during the Joule-Thomson expansion process, from entering the magnet cold mass. The amount of vapor in the cold mass is limited to that generated from heat leaks. The superconducting coil and bus are kept immersed in the liquid helium by controlling the liquid level in the end volume of the cold mass.

Beam screens are used to reduce the dynamic heat load to the beam tube and coil. The use of beam screen reduces the vapor flow inside the magnet cold mass. These beam screens will be provided and installed by CERN.

2. CRYOSTAT LAYOUT

The cross sectional view of the LBRS (D3a/D3b) cryostat is given in Figure 2. Each LBRS cryo-assembly consists of two cold masses side by side on a cradle and supported by three fiberglass-posts. They are surrounded by an aluminum heat shield. The vacuum vessel and the posts are identical to those used in the LHC arc dipole magnets. Outside of the cold mass there are five cold pipes, identified as:

- C' – the small beam screen supply line, which is used as a common supply for the two parallel beam screens.
- CL1 and CL3 – two cold mass supply lines for cooling the two side by side cold masses in parallel during cooldown and warmup.
- E – two pipes for the heat shield, only one of which is used in each location. The redundant arrangement allows the interchange of magnets between the left and right sides of IR4.

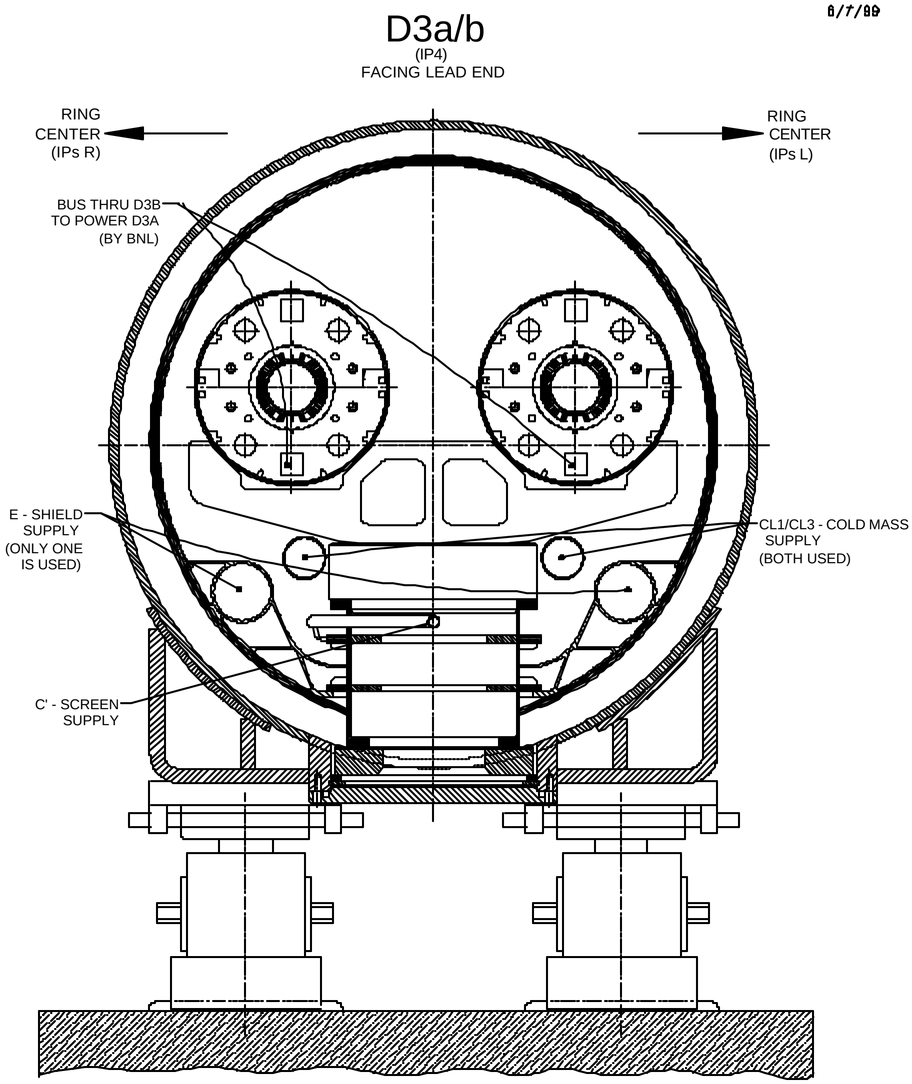


Figure 2. Sectional view of the LBRS (D3a/D3b) cryo-assembly

3. COOLING

3.1 GENERAL REQUIREMENTS

Heat load is a key parameter for a cooling system. In the LHC, the heat loads consist of two types, static and dynamic. The static heat load comes from conduction through the supports and radiation past the thermal insulation of the cryostat. The dynamic heat load comes from machine operation. The dynamic heat load consists of synchrotron radiation, imagine currents, beam scattering and photoelectron effects. For the LHC operating conditions, the dynamic heat load is large compared to that of the static heat load. The beam screen, operated between 4.5 and 20 K, is used to prevent majority of the dynamic heat load from entering the 4.5 K cold mass. There are three temperature levels of heat load for D3: 50-75 K of the thermal heat shield, 4.5-20 K of the beam screen and 4.5 K of the magnet cold mass.

3.1.1 STATIC HEAT LOADS

Static heat load of D3 is estimated by R. van Weelderen of CERN [5] and is given in Table 1. Heat loads for electrical splices, instrumentation feed throughs and cryogenic jumper lines are also included.

Table 1 Design Static heat load for D3 magnet

Source	***Heat Shield 50-75 K***	***Beam Screen 4.5-20 K***	***Cold Mass 4.5 K***
Supports	21.30	-	1.50
Thermal Shield (50-75 K)	27.62	-	-
Radiation to cold mass	-	-	1.00
Resistive heating (splices)	0.01	-	0.31
Instrument feed through	-	-	0.53
½ jumper	0	-	0.27
Total	48.93	0	3.61

3.1.2 DYNAMIC HEAT LOADS

The dynamic heat load is developed inside the beam tube. It does not reach the 50-75 K heat shield. An actively cooled beam screen is used to remove most of the dynamic heat loads that would otherwise be deposited in the 1.9 K magnet. The dynamic heat loads of D3 are estimated by CERN [5] for both the nominal and ultimate LHC operating conditions, and are given in Table 2. The heat loads for synchrotron radiation, image currents, beam scattering and photoelectrons are given in watts per meter. The photoelectron heat input depends on whether or not the region has magnetic field present. The length used in Table 2 is 10.23 m and includes the interconnecting piping. The field free region is about 0.78 m.

Table 2. Dynamic heat load of D3 at nominal and ulitmate operating conditions

Source	***Beam Screen Nominal***	***Cold Mass Nominal***	***Beam Screen Ultimate***	***Cold Mass Ultimate***
Synchrotron radiation (W/m)	0.200	0	0.302	0
Image Current (W/m)	0.192	0.005	0.438	0.011
Beam gas scattering (W/m)	0	0.050	0	0.050
Resistive heating-splices (W/m)	-	-		-
Photoelectron[a]				
-field region (W/m)	0.238	0	0.820	0
-field free region (W/m)	2.055	0	7.060	0
Total for 10.23 meter length[a]	7.86	0.56	20.83	0.62

Note: (a) From the mechanical layout drawings [6], the field region is taken as the magnetic length 9.45m. The total length is taken as the cold mass length 10.23 m. Their difference is taken as the field free region 0.78 m.

3.1.3 TOTAL HEAT LOADS

Total heat load equals to the sum of static and dynamic heat load and is given in Table 3. The cooling system must be designed for the maximum heat load of the D3 cryogenic module with a safety margin as shown in Table 4. Pressure and temperature at the 4.5 K supply line shall be 3 bar and 4.6 K. Pressure in the return line D is not expected to be greater than 1.3 bar during normal operation.

Table 3. Total heat load (Watts) for the D3 magnets at nominal and ultimate luminosity

	Heat Shield 50-75 K	***Beam Screen 4.5-20 K***	***Cold Mass 4.5 K***
Nominal			
Static (Table 1)	48.9	0	3.6
Dynamic (Table 2)	0	7.9	0.6
Total	48.9	7.9	4.2
Ultimate			
Static (Table 1)	48.9	0	3.6
Dynamic (Table 2)	0	20.8	0.6
Total	48.9	20.8	4.2

Table 4. Total heat load for the D3 cryogenic module

	Heat Shield ***50-75 K***	***Beam Screen*** ***4.5-20 K***	***Cold Mass*** ***4.5 K***
Nominal	97.8	15.8	8.4
Ultimate	97.8	41.6	8.4
Design value for cooling system	230	60	20

3.2 COOLING SCHEME

Both D3a and D3b have two cold masses. They are combined in one cryogenic module. The D3a and D3b are in series cryogenically. Inside each D3, the two side by side cold masses are cooled in parallel. The magnet leads for D3 face the DFB feed box, which is located between D3b and the D4 magnet. The D3 module is cooled by pool boiling of liquid helium at 4.5 K. The piping associated with pool boiling cooling is sensitive to the tunnel slope. The feed and the return lines should be implemented properly to ensure correct flow direction. The cryogenic feed is chosen in the high elevation end of the module and is connected to the LHC distribution line through piping spool QQS.

The flow diagrams for the left and the right side of IR4 are shown schematically below. Figure 2 illustrates the helium flows for the left side of IR4 and Figure 3 illustrates the flows for the right side. The dashed box in each schematic represents the responsibility of BNL.

3.3 4.5 K OPERATION

For steady state operation at 4.5 K, two phase helium from Header C is fed from both CL2 and CL4 lines in the high elevation end of D3. Vapor helium returns to Header D from LD1 and LD2 in the high elevation of. Liquid level is controlled from valves LCV1 and LCV2. The level gauges are installed in the end volume of the cold masses. Each string of cold mass is cooled independently of the other.

Note in the left side of IR4, magnet D3b is on the high elevation end and D3a is in the low elevation end. In the right side of IR4, D3a is on the high elevation end and D3b is in the low elevation end.

Table 5. Location of Helium Supply and Return lines Lines for the D3 Module

Item	***Elevation***	***Left Side of IR4***	***Right Side of IR 4***
Helium supply during cooldown	Low	D3a	D3b
Helium return during cooldown	High	D3b	D3a
Helium supply during operation	High	D3b	D3a
Helium return during operation	High	D3b	D3a

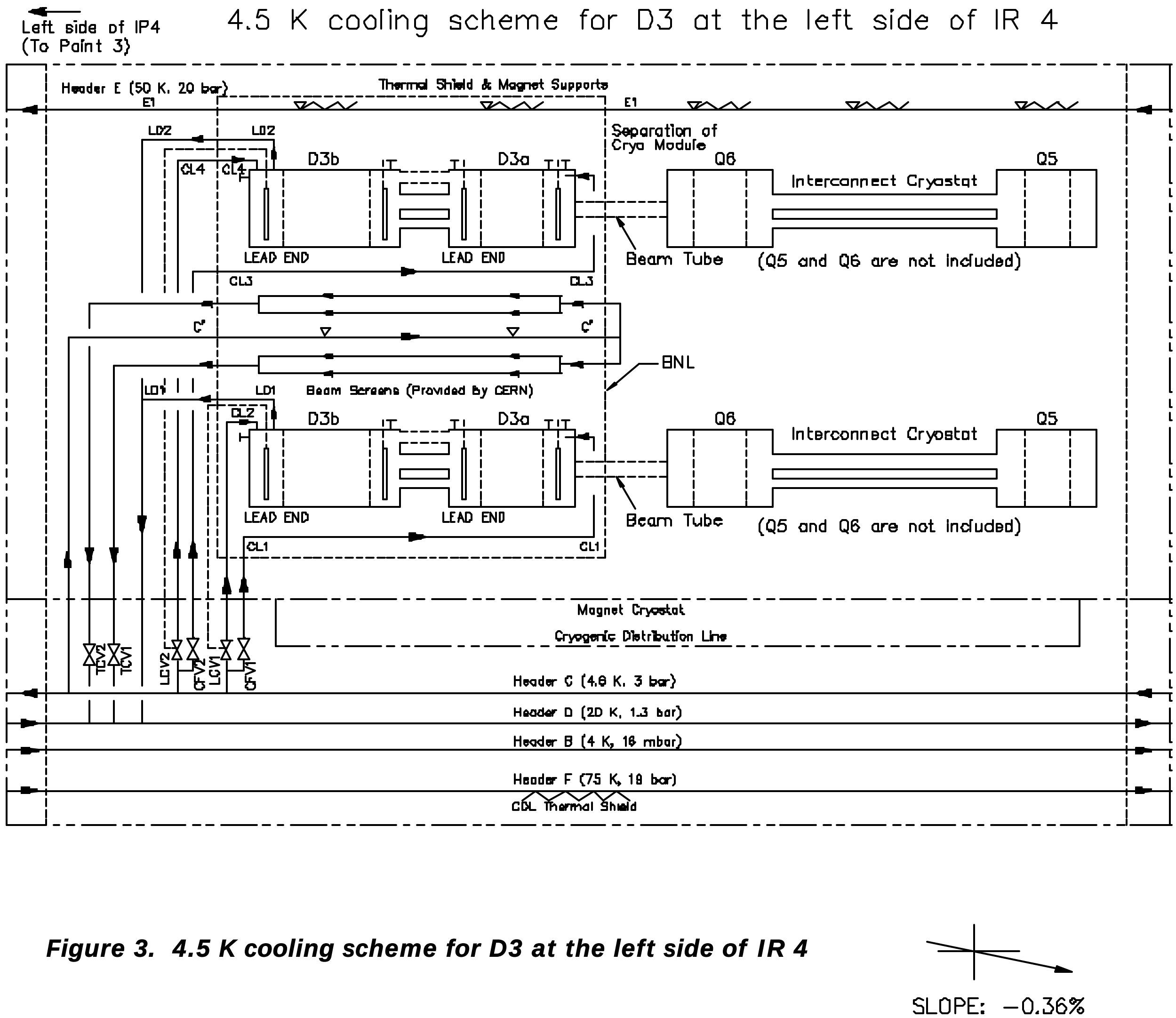


Figure 3. 4.5 K cooling scheme for D3 at the left side of IR 4

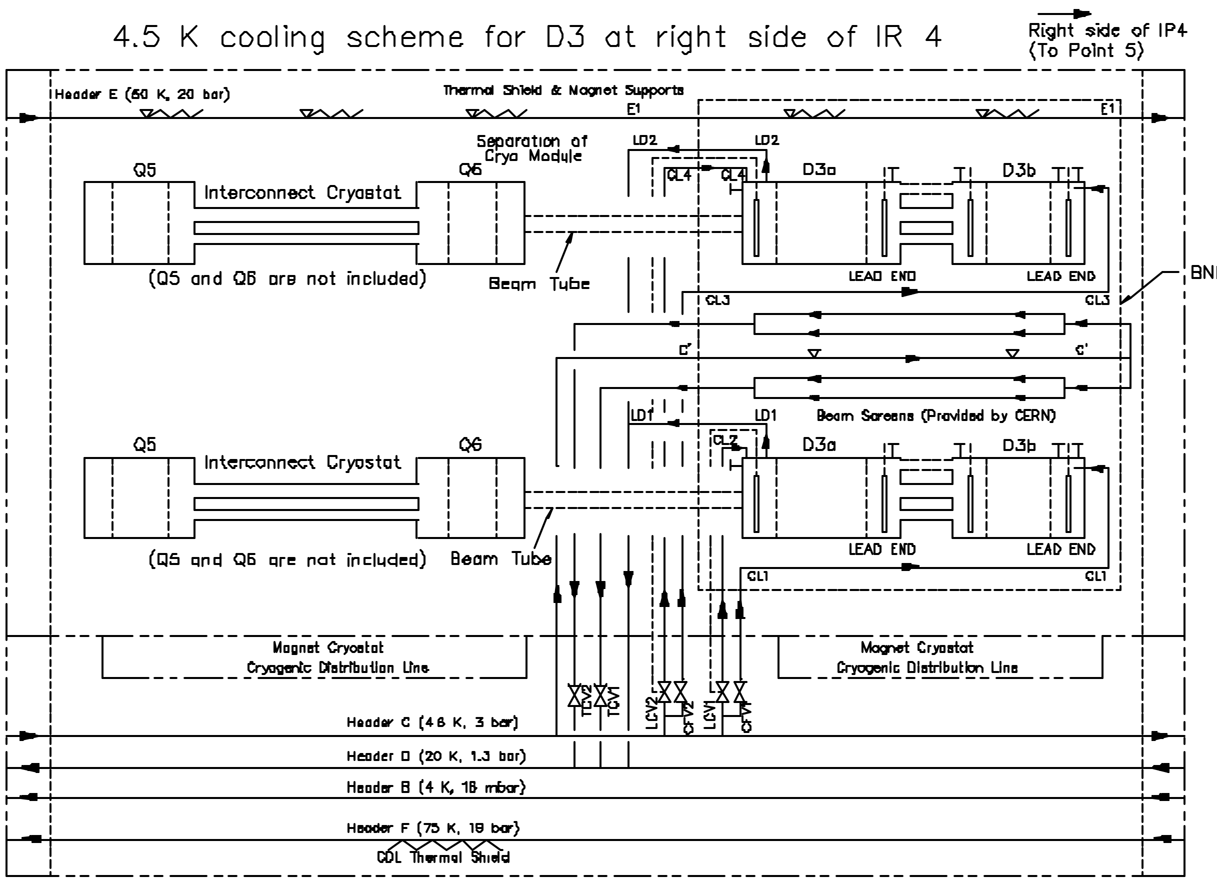
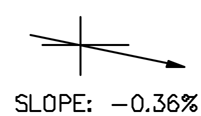


Figure 4. 4.5 K cooling scheme for D3 on the right side of IR 4



3.4 HEAT SHIELD COOLING

Heat shield cooling for the D3 cryogenic module is integrated into the shield cooling of the LHC arc magnets. The helium flow enters the module from the Q6 magnet. The shield flow passes one of the E lines in the LBRS to the DFB feed box. The shield temperature is controlled through a valve located in the middle of the LHC arc region.

3.5 COOLDOWN FROM 300 - 4.5 K

For cooldown from 300 – 4.5 K, helium from Header C flows in parallel, through CFV1 - CL1 and CFV2 - CL3, to the low elevation end of the module. Helium returns to Header D through the LD1 and LD2 lines from the high elevation end of the module. Each cold mass is cooled and controlled independently of the other. The temperature difference between the cooling helium and the magnet is expected to be kept below 50 K with a flow rate is about 50 g/s.

3.6 BEAM SCREEN COOLING

The beam screen cooling helium, flowing from the Header C through C' line, enters the low elevation end of the cryogenic module. It exits the high elevation end to Header D. Two temperature control valves, TCV2, are used to maintain each beam screen below 20 K. On the left side of IR4, magnet D3b is on the high elevation end and D3a is in the low elevation end. On the right side of IR4, D3a is on the high elevation end and D3b is in the low elevation end.

3.7 SAFETY RELIEF VALVES

No relief valves are allocated solely for the D3 cryogenic module. However, vacuum tank relief will be provided on each D3a and D3b cryostat. The 50-75 K cooling circuit of D3 is part of the LHC Sector heat shield cooling which has relief valves to handle the venting capacity of the entire circuit. There is no valve between the beam screen and Header C in the LHC distribution line. The relief valve in Header C can be used to vent helium in the 4.5-20 K cooling line. There is no valve between the D3 cold mass and Header D. Two phase helium in the D3 cold mass will be vented to the Header D should there is a pressure build up.

3.8 NOZZLES

Spare nozzles and level gauges in each end volume of each MBRS cold mass are shown In Figures 3 and 4. Each MBRS is constructed with extra nozzles and level gauges so that the magnet can be tested at BNL before being shipped to CERN.

3.9 CONTROL VALVES

Flow rates must be greater than 0.44 g/s for the 4.5-20 K beam screen cooling and 0.78 g/s for the 4.5 K magnet cooling. Flow control valves LCV1 and LCV2 should be slected for 1 g/s flow with 3 bar and 4.6 K at inlet, and 1.3 bar and 4.5 K at discharge. The percentage of liquid at discharge is estimated at 90 %. The flow control valves TCV2s should be designed for 1 g/s flow with 3 bar and 20 K at inlet. The discharge pressure and temperature are 1.3 bar and 20 K.

CERN will provide all valves. The operating and design conditions of these valves are given in Table 6.

Table 6. Operating conditions of the valves

	TCV2	LCV1 & LCV2
Inlet		
Pressure - bar	3	3
Temperature - K	20	4.6
Outlet		
Pressure - bar	1.3	1.3
Temperature - K	20	4.6
Liquid fraction - %		90
Mass flow – g/s		
Operating condition	0.44	0.78
Design value	1	1

4. REFERENCES

1. "LAYOUT OF LHC LONG STRAIGHT SECTIION VERSION 6.2", LHC Drawings LHCLSX_0007 and LHCLSX_0008 (IR4).
2. "Superconducting Beam Separation Dipoles", LHC Functional Specification, LHC-MBR-ES-0001.
3. "LBRS Cryo-assemblies – D3 Dipoles", LHC Interface Specification, LHC-MBR-ES-0005.
4. "Cooling Scheme for BNL-Built LHC Magnets", K. C. Wu, S. R. Plate, E. H. Willen, R. van Weelderen, R. Ostojic, presented in the 1999 Cryogenic Engineering Conference, Montreal, Canada.
5. Rob van Weelderen, Web publication, http://vanweeld.home.cern.ch/vanweeld/heatload/hlmagnets.html
6. "LAYOUT OF LONG STRAIGHT SECTION VERSION 6.2," LHC Drawings LHCLSX__0007 and LHCLSX__0008 (IR4).